

# Short-duration lensing events: II. Expectations and Protocols

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## ABSTRACT

Ongoing microlensing observations by OGLE and MOA regularly identify and conduct high-cadence sampling of lensing events with Einstein diameter crossing time,  $\tau_E$ , of 16 or fewer days. Events with estimated values of  $\tau_E$  of one to two days have been detected. Short duration events tend to be generated by low-mass lenses or by lenses with high transverse velocities. We compute the expected rates, demonstrate the expected ranges of parameters for lenses of different mass, and develop a protocol for observing and modeling short-duration events. Relatively minor additions to the procedures presently used will increase the rate of planet discovery, and also discover or place limits on the population of high-speed dim stars and stellar remnants in the vicinity of the Sun.

## 1. Introduction

The work described in this paper is inspired by the success achieved by the OGLE (Udalski 2003) and MOA (Bond et al. 2001) teams in discovering and monitoring events of short duration. Short-duration events now constitute a significant fraction of all event candidates. For example, approximately 9% of 654 recent events listed by the OGLE team on its *Early Warning Site* (EWS; <http://ogle.astrouw.edu.pl/ogle3/ews/ews.html>) have Einstein-diameter crossing times shorter than 8 days. Twenty-seven percent of these short events have  $\tau_E < 4$  days, and a handful have  $\tau_E < 2$  days. While not all of the candidate events of short duration are likely to be lensing events, many of the light curves appear to be well fit by lensing models. The prospects for increasing the rate of discovery of short-duration events are good. Ongoing programs are continuing to implement improvements, while new projects are starting or being planned.

The value of  $\tau_E$  is an estimate of the time during which the gravitational magnification would exceed 1.34 for close approaches between the source and lens. Current observing programs are sensitive enough to detect ongoing events when the magnification is just a few percent, increasing the effective event duration by a factor that can be as large as 3.5.<sup>1</sup> These programs are therefore able to call alerts on ongoing events with small values of  $\tau_E$ . Just as alerts on events deemed likely to produce caustic crossings inspire world-wide “follow-up” with more frequent observations (see Griest & Safizadeh 1998), alerts on short-duration events can be accorded high priority. The goal is to collect enough data to permit detailed model fits.

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<sup>1</sup>For heavily blended events, or events in which the peak magnification is low, the enhancement factor will be smaller (Di Stefano & Esin 1995).

The scientific advances made possible by studying short events are significant. The systematic study of short-duration events will yield information about brown dwarfs, planets orbiting stars, as well as free-floating planets<sup>2</sup> and hypervelocity objects. In the companion paper we explored the benefits of selecting for intensive study events of short duration (DiStefano 2009). Here we develop strategies that can help monitoring programs to discover planets, brown dwarfs, and hypervelocity objects.

In §2 we estimate the rate of such events, relative to the rate of all detected events in both present and future monitoring programs. We demonstrate that the rate is high enough that existing data contain evidence of hundreds of interesting short-duration events. More important, every year an additional  $> 100$  short-duration events should be detected. These can be followed in real time, maximizing the science return from each. In §3 we consider the relationship between event characteristics and the location of the lens, and give some explicit examples of model tests that are possible under ideal circumstances. These brief sketches integrate the measurements discussed in the companion paper. Section 4 reviews the prospects for optimizing, in the immediate future, what we can learn about planet lenses and the other intriguing masses that can generate events of short duration.

In the appendix we point out that short-duration events caused by wide-orbit planets, free-floating planets, and hypervelocity objects will be augmented by short-duration events expected when the lens is a planetary system with close-in planets. The orbital separations in some of these additional cases put the planets in the habitable zone (DiStefano & Night 2008).

## 2. The Rate of Short-Duration Events

### 2.1. Estimates

The populations producing short-duration events are comprised of objects that are not yet well-studied. Predictions of the rates at which they should produce events therefore have large uncertainties. We have used a simple and straightforward approach which allows the effects of each assumption to be traced, so that adjustments can be easily made if necessary.

We assumed that the majority of lensing events presently detected are generated by stars, and that the majority of stellar-lens events are generated by M dwarfs. If the rate at which M-dwarf events are detected is  $\mathcal{R}$ , then the rate of detected events caused by other types of lenses can be obtained by scaling according to lens mass, transverse velocity, and spatial density. This was carried out in DiStefano 2008b for brown dwarfs and stellar remnants. Those calculations produced the relative rates of events shown in column 1 of Table 1, for brown dwarfs, white dwarfs, neutron stars, and black holes.

Main sequence stars more massive than M dwarfs also cause lensing events. To compute the rate at which they generate events, relative to the rate at which M dwarfs generate

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<sup>2</sup>Any planet-mass object not bound to a star will be referred to as a *free-floating planet* in the rest of the text. Some such low-mass objects may have been formed in and ejected from planetary systems, and others may have been formed in isolation.

events, we simulated a population of stars using the Miller-Scalo mass function. By using the fact that the rate at which each star produces lensing events scales as the square root of its mass, we found that stars with masses above  $0.5 M_{\odot}$  produce approximately as many events as stars of lower mass, even though the mass function declines with increasing mass. Because, however, more massive stars are more luminous than M dwarfs, events generated by them can be more difficult to detect, even if image differencing is employed. We therefore assume that, while events by both nearby and more distant M dwarfs contribute to the events discovered by the OGLE and MOA teams, only more distant stars of larger mass contribute. We therefore took the total rate of detectable lensing by stars to be  $1.5 \mathcal{R}$ , with stars more massive than M dwarfs contributing  $1/3$  of the total.

In addition, planets in wide orbits produce events. The average rate per star is  $\sqrt{M_*} \sum_i \sqrt{q_i}$ , where the sum is over the number of wide-orbit planets, and  $q_i = M_{\text{planet},i}/M_*$ . Here we will assume that the rate of planet-lens events is 15% the rate of M dwarf events. The rate at which the outer planets of our solar system generate events, compared to the rate of events due to a star of  $0.25 M_{\odot}$  is roughly 0.12. Many stars appear to have planets more massive than Jupiter, however, and some of these appear to be in very wide orbits<sup>3</sup>. Free floating planets are likely to add a significant contribution. Although the value of 15% is uncertain, the true rate seems likely to lie within a factor of 2 of it.

As the companion paper demonstrates, planet-lens events are likely to be the shortest events. They are therefore more likely to be missed by present-day monitoring teams. In Table 1 we assume that the efficiency for detecting events by planet-mass lenses is only half that for longer-lasting events. As we will discuss in §4, however, some future programs will improve the efficiency of detecting short-duration events. In Table 1 we therefore include a column for “future” monitoring programs which achieve equally good efficiencies for short and long events.

Among high-velocity objects, we have included computations only for neutron stars, because we can make rough but reasonable estimates based on the inferred galactic population of neutron stars. Other high-velocity objects can be expected to supplement these numbers; these include dim halo stars and remnants of runaway and hypervelocity stars.

### 2.1.1. Implications

The numbers of events predicted in Table 1, though approximate, provide guidance for what we can expect from existing and future data sets. Column 4 of Table 1 shows that we can expect 124 short events among each 1000 events (Column 3). We therefore expect that, at present,  $\sim 12\%$  of all detected events should have  $\tau_E < 16$  days. This is roughly consistent with the data on the OGLE team’s web site, although we don’t know the fraction of the posted events actually associated with lensing. Nevertheless, it is likely that existing data sets, which include more than 4000 event candidates, contain evidence for roughly 500 short-duration events. Seventy percent of these are likely to have durations in the range 8 – 16 days. Of these,  $\sim 80\%$  were caused by brown dwarf lenses, and the remainder by high-velocity stellar remnants. The majority of the shorter events were caused by planets.

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<sup>3</sup><http://exoplanet.eu/>

Although we do not have an opportunity to improve upon the sampling of events that have already occurred, we can nevertheless conduct meaningful tests and identify the natures of at least some of the lenses. We should check existing multiwavelength catalogs and data sets at the position of each event well-sampled enough that we are reasonably confident (a) it corresponds to microlensing and (b) that the short duration is not due to blending. In at least some cases we should find evidence for an object that is not the lensed source, but which could instead be part of the lens system. In cases where there is a match, the possible contributions of additional observations, including some with HST, should be considered. It would be surprising if a comprehensive analysis of already-discovered short events does not reveal the presence of a set of interesting lenses.

The existing data sets are almost certainly minute in comparison with future data sets, which will discover more events per year. Column 6 of Table 1 shows that we can expect 150 short events among each 1000 events (Column 5) detected by monitoring programs sensitive to short events. The challenge ahead is, therefore, to institute real-time recognition of short-duration events to immediately identify those that are promising candidates for additional observations. We discuss this further in §6.

### 3. Learning about the Lens

#### 3.1. Lens Location and Finite-Source Size

For each type of lens defined by a given mass range, the selection of short-duration events corresponds to a selection of lenses in one of two distance regimes. This is because the equation for  $D_L$  is quadratic, generally admitting two solutions,  $D_L^+$  and  $D_L^-$ .

$$D_L^\pm = \left(\frac{D_S}{2}\right) \left[1 \pm \sqrt{1 - 4 \left[\frac{\tau_E}{0.68 \text{ d}} \frac{v}{75 \frac{\text{km}}{\text{s}}}\right]^2 \left[\frac{8 \text{ kpc}}{D_S}\right] \left[\frac{M_\oplus}{M}\right]}\right] \quad (1)$$

For lenses that are brown dwarfs, planets, and neutron stars,  $D_L$  is shown as a function of  $v$  in Figures 1 through 3, respectively.  $D_L^-$  can be in the range of tens or hundreds of pc. When the lens system is this close to us, the probability of being able to detect it is large. As discussed in the companion paper, the degeneracy inherent in lensing can therefore often be broken. In fact, for a given lens, there may be several different ways of measuring the some key quantities, such as the mass of the planet-lens (see, e.g., §3.2).

Because nearby lenses can be so well studied, we can use them to make predictions for the population of distant lenses, with  $D_L = D_L^+$ . Nearby lenses producing short-duration events can be identified as planets, brown dwarfs, or stellar remnants. If we assume that stellar populations in the dense source systems contain similar populations, we can predict the distributions of values of  $\tau_E$  and also of values of  $\theta_E$ . ( $\theta_E$  is more likely to be measured for  $D_L = D_L^+$ ). Comparisons between the predicted and observed distributions will allow us to test models.

Note, in addition, that for a given lens mass and speed, the requirement that  $D_L$  be real, places an upper limit on the Einstein diameter crossing time.

$$\tau_E < 0.34 \text{ d} \left(\frac{75 \frac{\text{km}}{\text{s}}}{v}\right) \left[\frac{M}{M_\oplus}\right]^{\frac{1}{2}} \left[\frac{D_S}{8 \text{ kpc}}\right]^{\frac{1}{2}} \quad (2)$$

Thus, for the values of  $v$  expected for planets, Earth-mass planets (dwarf planets) can produce only events shorter than about a day (an hour), while events generated by Jupiter-mass planets should have  $\tau_E$  less than roughly 18 days. In order for higher-mass lenses (such as brown dwarfs) to produce short events, they must be very nearby or else very close to the source (Figures 1 and 3). Although there are fewer lenses in these small volumes, each of the nearby lenses has a relatively high probability of generating an event because values of both  $\theta_E$  and  $\omega$  tend to be high (Di Stefano 2008b).

### 3.2. Examples

In many cases, particularly for mesolenses, it is possible to productively follow several different lines of evidence to learn more about the lens system. In the companion paper we considered free-floating planets. Below we consider examples of brown dwarfs, bound planets, and high-velocity stars.

#### 3.2.1. Brown Dwarfs

The first examples we consider are nearby brown dwarf lenses. It is important to note that two particularly exciting candidate brown-dwarf events have been detected within 6 months of each other, both with  $\tau_E < 16$  days. The first of these was detected serendipitously by an amateur astronomer, A. Tago, searching for novae. The Tago event was the first lensing event discovered in a sparse field, through monitoring not specifically designed to find evidence of lensing. The lensed source is an ordinary A0 star located a kpc away, clearly indicating that the lens is nearby. The event was of short duration, with the Einstein-diameter crossing time estimated to be in the range 10 – 15 days (Fukui et al. 2007) and an estimated peak magnification of about 50. Gaudi et al. (2008) find that the most likely explanation for this event is lensing by a nearby brown dwarf with a proper motion greater than or approximately equal to  $20 \text{ mas yr}^{-1}$ . Because the source star was so bright, Fukui et al. (2007) were able to verify one of the fundamental properties of lensing predicted by Einstein’s theory, that the spectrum is unchanged by lensing. In this case, we still know little about the lens, in spite of its apparent proximity. During the course of the next decade, however, the lens and lensed source should separate by a large enough angle that they can be resolved by JWST, which is scheduled to be launched within the next 5 years. The IR sensitivity of JWST, combined with its angular resolution will allow it to detect the lens, if the lens is a brown dwarf. The angular separation achieved at the time of the observation will provide a value of  $\omega$ . The combination of  $\omega$  and  $\tau_E$  will yield the value of  $\theta_E$ . If the flux and spectrum of the brown dwarf allow the photometric parallax to be determined, the brown dwarf’s mass will be derived. Otherwise, a sequence of additional images will determine the geometric parallax, thereby allowing us to measure the lens mass.

Six months after the Tago event, a second short-duration event that was most likely caused by a brown dwarf was observed. This event had a peak magnification larger than 1000. Both parallax and finite-source-size effects were detected, allowing the mass ( $0.056 \pm 0.004 M_\odot$ ) and distance to the lens ( $525 \pm 40 \text{ pc}$ ) to be determined. The transverse velocity

of the lens is  $113 \pm 21 \text{ km s}^{-1}$  (Gould et al. 2009).

The discovery of these two brown dwarf events is remarkable because each event had a high magnification, and therefore required a very small distance of closest approach. Such events are therefore rare. Each of the two events therefore represents a large number of additional brown-dwarf events of short duration. It would be difficult to use the detection of these two events to formulate a realistic estimate of the total number of short-duration brown-dwarf-lens events presently expected. Nevertheless, these detections add plausibility to the estimates we have made above, based on rate calculations and the combined OGLE and MOA detection rates.

Figure 1 demonstrates that brown-dwarf events with  $\tau_E$  in the range of 8–16 days can take place at distances greater than a hundred pc for velocities in excess of  $\sim 50 \text{ km s}^{-1}$ . Note in addition, that the total volume, hence the number of possible lenses and the rate of lensing by any given population of lenses, increases with distance from us. (See, e.g., DiStefano 2008a, 2008b for details.) Therefore the largest number of brown-dwarf lenses generating 8–16-day events should have velocities  $> 50 \text{ km s}^{-1}$  and be located at distances larger than 100 pc. This is consistent with the events observed to date.

### 3.2.2. *An ideal planet-lens case*

Consider a planetary system in which one planet serves as a lens, producing a short-duration event with a measured value of  $\tau_E$ . Suppose that the star orbited by the planet lens is detected. Suppose further, that a sequence of high-resolution measurements allows the geometric parallax, proper motion, and Einstein angle of the star to be measured (see, e.g., DiStefano 2009). The combination of  $D_L$  and  $\theta_{E,*}$  produces a high-precision value of the gravitational mass,  $M_*$ , of the star. In general, the stellar mass is estimated based on spectral and flux information. A direct measurement of the gravitational mass allows stellar models to be tested. In some cases, it may be possible to conduct subsequent transit or radial-velocity studies to measure the gravitational mass of the star in a second way, i.e., by studying the orbit of the planet that served as a lens and/or the orbits of other planets. Thus, for some stars orbited by planet lenses, we may be able to compare the gravitational mass measured via lensing with the gravitational mass measured via orbital dynamics.

Up to this point in our discussion, the planet has played only a peripheral role: (1) it produced a photometric event that alerted us to the possibility of measuring astrometric lensing by the star, and (2) it alerted us to the presence of at least one planet orbiting the star, thereby motivating subsequent transit and/or radial-velocity studies. The lensing event can of course teach us a good deal about the planet.

First, if finite-source-size effects are detected, then  $\theta_{E,planet}$  can be directly measured. The distance to the planet is, to high precision, the same as the distance to the central star. The combination of  $\theta_{E,planet}$  and  $D_L$  measures the mass of the planet. With the gravitational masses of both the planet and star measured, the mass ratio  $q$  can be computed.

If, in addition, the projected orbital separation,  $a$ , between the central star and planet lens is less than roughly  $3.5 R_{E,*}$ , or if the event “repeats”, then  $q$  and  $a$  can both be estimated from a fit to the planet-lens light curve. The value of  $q$  so measured can be

checked for consistency with the measured values of the planet’s and star’s gravitational masses.

The projected orbital separation,  $a$ , measured from the light curve, can be related to a combination of the true orbital separation at the time of the event and the orbital inclination:  $a = a_{true} \cos(\theta)$ . The value of  $a_{true}$  is related to the orbital speed at the time of the event:  $v = 30 \text{ km/s} \times \sqrt{(M_*/M_\odot) (\text{AU}/a_{true})}$ .

The proper motion of the planet can be measured from a combination of  $\theta_{E,planet}$  and  $\tau_E$ . With  $D_L$  known, we can estimate the projected value of the planet’s orbital velocity,  $v \cos(\theta)$ , by comparing the values of  $\omega_{planet}$  and  $\omega_*$ . Combining the equations for  $v$  and  $a$ , yields a value for the inclination of the orbit.

This example illustrates that for nearby lenses, orbital solutions can be obtained, even for face-on orbits. Furthermore, there can be enough information to provide independent checks on the values of some physical parameters. Even planets in very wide orbits can be well studied with lensing, especially if there is a repeating event (DiStefano & Scalzo 1999b).

### 3.2.3. High-velocity Stars

When high-velocity stellar-mass objects are nearby, their Einstein angles are large enough to be measured during the event by measuring the centroid shift in the lensed source. In general, this leaves a degeneracy between  $D_L$  and  $M$ . The degeneracy can be resolved if the lens is detected. Consider, for example, a halo dwarf star with  $M = 0.25 M_\odot$  and  $v = 180 \text{ km s}^{-1}$ . If this lens is 34.8 pc away from us, it can cause an event with  $\tau_E = 5$  days. Assuming that  $D_S \gg D_L$ , The value of  $\theta_E$  would be 7.6 milliarcseconds, and the astrometric shift induced by the lens could be measured; the optimal case would be when the lensed source is a bright blue star. Such a halo dwarf would itself be easily detected after moving from the source position, and its proper motion and parallax could be directly measured. Its gravitational mass could therefore be measured to high precision. This lens would travel across the sky with an angular speed of  $\sim 1'' \text{ yr}^{-1}$ . With such a high angular speed. it is very likely that, if the background field is dense, additional lensing events will occur over a time interval of  $\sim 10$  years. Because the presence of the lens is already known, it is easier to identify future events with confidence, even if the angle of closest approach is larger. Once a second event is discovered, the general direction of the lens motion is known and future photometric and astrometric events are more easily predicted. If a sequence of events is detected, the proper motion and parallax can be computed by comparing the locations and times of the events. This means that even for dark high-speed lenses, mass measurements can be made. When the lens is a neutron star, it may radiate x-rays as it cools and/or accretes matter from the ISM; it may therefore be catalogued as a weak x-ray source. It is worth noting that repeating events have been observed (Skowron et al. 2009).

## 4. Science, Strategies and Prospects

### 4.1. Science Goals

Every event of short duration is likely to be associated with an interesting lens: a low-mass object, or a high-velocity mass. These events should therefore be high-priority targets for intense monitoring and follow-up, even when the value of the peak magnification is modest. The choice of the range of values of  $\tau_E$  on which to spend the greatest resources must be governed by the science goals of the investigators.

#### 4.1.1. Planets

While any set of short events is likely to include planet-lens events, the set of the shortest events, those with  $\tau_E$  less than roughly 4 – 8 days, is likely to consist primarily of planet-lens events. The returns for studying these events of very short duration are potentially large. Because the numbers of planets with  $a > 1.5 R_{E,*}$  is larger than the numbers in the narrow annulus within which the so-called “resonant” events are generated, the rate of planet discovery by lensing will increase when concerted efforts to discover and study short events are made. We note further that the wide-orbit planets are almost certainly augmented by a significant number of free-floating planets.

The potentially large contribution of wide-orbit planets to short and repeating lensing events was noted more than a decade ago (Di Stefano & Scalzo 1999a, 1999b). At that time, however, the set up of the monitoring and alert observing programs was not well suited to the study of short-duration and repeating events. A decade of advances in the observing programs has put in place the ingredients needed to detect and identify short-duration and repeating events. Furthermore, the more sensitive photometry used today will play an important role in increasing the detection efficiency (Di Stefano & Scalzo 1999a, 1999b).

In addition, as we note in the appendix, in the near future, short events could begin to be routinely identified in cases in which the planetary separation is small:  $a < 0.5 R_{E,*}$ . These events present the exciting possibility of using lensing to find nearby planets in the habitable zones of their central stars (Di Stefano & Night 2008).

In fact, as we have shown in the companion paper, choosing short-duration events tends to select nearby lenses as well as lenses very close to the source star. The nearby planets that are identified through their actions as lenses can be among the best-studied and will become touchstones in the field of planetary studies.

#### 4.1.2. Brown Dwarfs and High-velocity Stars

Events of 8 – 20 days are more likely to have been induced by brown dwarfs or fast moving stars. The discovery of nearby neutron stars would, by itself, be of great scientific value. The same is true of hypervelocity stars, runaway stars, and their remnants. Gravitational mass measurements of neutron stars and other stellar remnants, as well as of brown dwarfs, would advance our knowledge of fundamental science. The feasibility of mass measurements has been demonstrated in several cases (In addition to Gould 2009,



see Alcock et al. 2001; Gould 2004; Gould, Bennett, & Alves 2004; Drake, Cook, & Keller 2004; Nguyen et al. 2004.) The mass functions of brown dwarfs and stellar remnants have not yet been well established. In addition, having a set of nearby objects would allow more detailed studies of the relevant equations of state.

## 4.2. Observing Programs

Because monitoring teams are already identifying short-duration events, identification of planets, brown dwarfs, and high-velocity stars can start immediately. This is demonstrated by Gould et al. (2009), although for an event that had a duration on the longer end of “short-duration” events. Current programs could discover, every year, 45 – 69 short events caused by brown dwarfs, 23 – 36 short events caused by wide-orbit planets, 8 – 13 short events caused by high-speed neutron stars, and perhaps additional events caused by hypervelocity stars or their remnants. Comprehensive model tests of a large fraction of these events, including the planet events, will be possible. Nearby planetary systems (12-18 per year) may be susceptible to follow-up observations, including radial velocity or transit studies.

Pan-STARRS is about to begin taking data over a large region using several sampling strategies (Chambers et al. 2004). For example, regular monitoring will take place over roughly 70 square degrees in its Medium Deep Survey. Additional wide-field coverage will eventually be provided by LSST, which will cover  $\sim 20,000$  sq. degrees every three to four nights. While the cadence of these programs is not ideal for the detection of short events, the efficiency for the detection of events caused by brown dwarfs, high-velocity stars, and the most massive planets will be high. Once identified by wide-field monitoring programs, more frequent follow-up is required to fully characterize the light curve. For events of shorter duration, the efficiency of event detection and identification will be lower. If, however, as part of each independent scan, different filters are used in a sequence over a time interval during which the magnification is changing, even very short-duration events could be identified as targets for more frequent monitoring. The maximum value of the efficiency would be:  $f \tau_E / \Delta t$ , where  $f$  is a number in the range 0.1 – 1,  $\Delta t$  is the time between distinct sequences of observations. In LSST and portions of the Pan-STARRs fields,  $\Delta t$  will be 3 – 6 days. Even efficiencies of a percent are significant, because the total area monitored will be large enough that many lensing events are expected, in front of both dense and sparse fields (Di Stefano 2008b, Han 2008).

It is likely that, within five years, a program ideal for the detection of short-duration events will begin. Funding was recently approved for the *Korean Microlensing Telescope Network (KMTNet)*, which plans to use 3 telescopes across the Southern Hemisphere to provide monitoring with 10-minute cadence of approximately 16 sq. degrees (Han 2009). As Figure 2 shows, KMTNet can provide excellent monitoring for Earth-mass planets. It could even discover dwarf planets with Einstein-diameter crossing times of less than an hour, although in such cases, follow-up by other observers would be required to obtain good sampling.

### 4.3. Protocols

Below we summarize the steps that can be taken in the immediate future by monitoring teams already in action. At the end of the section we discuss work that could be conducted with archival data.

- The first step is to increase the effective cadence, to increase the chances of identifying events of short duration. Cooperation among teams, e.g., the MOA and OGLE teams could effectively increase the cadence of monitoring in selected fields.

The philosophy of microlensing monitoring has been based on the premise that events are generated by lenses that are not known *a priori*. For mesolenses, though, this is not always the case. For example, when the lens producing a short-duration event happens to be a planet in orbit with a nearby star, there is a good chance that the star has already been detected, especially when the region has been monitored over an interval of years.

- To facilitate the identification of all events in which radiation from a component of the lens system can be detected, it is important for monitoring programs to develop automatic links to multiwavelength data bases that catalogue objects that might correspond to the lens. Stellar remnants may have been detected at X-ray wavelengths, brown dwarfs in the infrared, stars orbited by planets at optical and/or infrared. We note that, although this step is important for short events, it is also potentially very useful even for longer events. Whatever the event duration, this step will identify those events caused by nearby lenses, facilitating high-precision measurement of the lens mass. Ideally, in addition to the catalogues, the monitoring teams should have quick access to the data taken at various wavelengths, since many nearby sources may not have been catalogued.
- When a short-duration event is caused by a planet orbiting a star, and when the planet-star separation is less than roughly  $3.5 R_{E,*}$ , the presence of the star would already have caused a gradual increase in the magnification, even before the short-duration event caused by the planet. Monitoring teams can test for such a prior trend at the start of what appears to be a short-duration event.
- “Repeating” events in which a planet and its star serve as independent lenses are expected in as many as  $\sim 10\%$  of events in which a star with a planetary system serves as a lens. (See DiStefano & Scalzo 1999b.) The most likely case is the one in which the planet lens producing the shorter event of the two events is the innermost “wide” planet. Roughly half the time, the star should have produced the first event. Any short duration event that follows a stellar-lens event has a good chance of having been produced by a planet in orbit with the star. It would be worthwhile to subject the declining portion of each stellar-lens event to monitoring capable of quickly identifying subsequent short events. For planets with masses comparable to or larger than the that of the Earth, monitoring 1 – 3 times per day would be adequate to identify any additional perturbations that occur either as the stellar-lens event declines or with  $\tau_E$  of the return to baseline. An alert should be called immediately when such deviations are detected. It is important to note that

systematic monitoring of this type will either yield planet detections (the most likely outcome) or will allow meaningful limits on the structure of planetary systems to be derived.

- High-resolution images can play an important role for a wide range of lenses producing short-duration events. The possible uses of such imaging are described in §3 and in the companion paper. In some cases, it is important to obtain an image soon after the event is identified. In others, images taken years after the event may be useful. By using the light curve sampling and archived data to identify the most promising models, observers can identify those cases in which HST or JWST may provide key information about the lens.
- When an ongoing event is identified as a possible short-duration event, an alert should be called. Ground-based multiwavelength observations with good angular resolution, taken as the magnification increases, can establish the amount of blending and determine if the short duration of the event is an artifact caused by blending. If so, monitoring for the reasons explored in this paper is no longer necessary. Events that are genuinely short should be subject to intensive monitoring by a global network of telescopes. In some cases, the monitoring programs may themselves sample the light curve frequently enough to allow good model fits. Model fits to a well-sampled light curve can determine the values of  $\tau_E$ ,  $b$ , and discover whether finite-source-size effects, the existence of a companion, and even parallax effects influence the light curve shape. The cadence of monitoring should be greatest near peak, even if the magnification is not high.

Finally, we note that it is not always possible to follow each event as it unfolds. This is certainly the case for events that have already occurred. Even future monitoring programs, with their improved detection efficiencies, may not identify or be able to follow all short-duration events in real time. In these cases, light curve fits to the short-duration event, including possible long-term deviations from baseline that could “frame” the short-duration event, can be carried out. In addition, step 2 above (studying multiwavelength catalogs and data that cover the region around the event), can provide important information. In some cases, follow-up HST imaging can also be used to test models, e.g., allowing the lens mass to be determined in some cases.

## 5. APPENDIX: Very Close Planets and the Habitable Zone

In the context of planetary systems, independent events of short duration were originally predicted for planets in wide orbits ( $a$  greater than roughly  $1.5 R_{E,*}$ ). Recently, however, close orbits ( $a < 0.5 R_{E,*}$ ) were studied, and a second class of short-duration event considered (Di Stefano & Night 2008).

For small  $a$ , there are two regions in the lens plane where the effects of the planet are significant. The first is close to the central star. Events in which the source track passes close to the star therefore exhibit short-lived deviations from the point-lens form. As the value of  $a$  decreases below  $0.5 R_{E,*}$ , the region of perturbations caused by the planet

becomes smaller. Consequently the deviations in the light curve are shorter-lived and are also more easily washed out by finite-source-size effects. The second region is at a distance of roughly  $1/a$  from the star, along the binary axis. (See Di Stefano & Night 2008). This region has a small caustic, which has little effect on most light curves. There is a region around the caustic, however, in which the deviation from the low-magnification effects of the star can be as large as a few percent, lasting from hours to days.

KMTNet will be very sensitive to these deviations. But even today’s monitoring programs could find them. To do so would be important, because for nearby M dwarfs, orbital separations of  $0.2 - 0.5 R_{E,*}$  put the planet in the zone of habitability.

The teams could call alerts on such events with a high level of confidence because of the presence of the star along the line of sight and also because a low-magnification effects associated with the star, frame the short-duration deviation caused by the planet. This is in exact analogy to the situation in which a short-duration event is caused by a planet with  $1.5 R_{E,*} < a < 3.5 R_{E,*}$ .

There are several new features of lensing in this close-planet regime.

- (1) The deviation that signals the presence of the planet is not generally well approximated by a point-lens model.
- (2) The deviation that signals the presence of the planet occurs when the source is far from the central star ( $\sim 1/a$ ).
- (3) Because the planet is close to the star, orbital motion can be significant during the event. This means that the regions of deviation are likely to swing into the path of the source star. We have found that the rate of these potentially important events can be comparable to the rate of stellar-lens events exhibiting  $A > 1.34$ .

We therefore expect that, ultimately, events in which we can find evidence of a planet orbiting close to the central star, potentially in the habitable zone, could be an important addition to short-duration events.

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Table 1: Numbers of Short-Duration Events ( $\tau_E < 16$  days)

Lens Type	Relative Event Rate	Number of events per 1000 detected <i>Present</i> <sup>(1)</sup>	Number of short events per 1000 detected <i>Present</i>	Number of events per 1000 detected <i>Future</i> <sup>(2)</sup>	Number of short events per 1000 detected <i>Future</i>
M dwarfs	1.0	481	5 <sup>(3)</sup>	465	5
Other stars	0.5	241	0	233	0
Brown dwarfs	0.19	92	69	88	66
White dwarfs	0.17	82	0	79	0
Neutron stars	0.13	63	13	60	12
Black holes	0.01	5	0	5	0
Wide-orbit planets	0.15 <sup>(4)</sup>	36	36	70	70

NOTES: <sup>(1)</sup> *Present* refers to the number of events generated by each type of lens per 1000 events detected by monitoring programs with the capability of OGLE III. <sup>(2)</sup> *Future* refers to the number of events generated by each type of lens per 1000 events detected by monitoring programs of the future which will be more sensitive to events with  $\tau_E < 2$  days. <sup>(3)</sup> We assume that roughly 1% of all events generated by M dwarfs will have  $\tau_E < 16$  days). These correspond to very fast transverse velocities or M-dwarf lenses very close to us. More massive stars that are close to us may be too bright to generate events detectable by the monitoring programs. <sup>(4)</sup> We assume that only half of these are long enough to be detected by today’s monitoring programs, but that programs of the future, such as KMTNet (see §4.2) will be able to detect most planet-lens events.

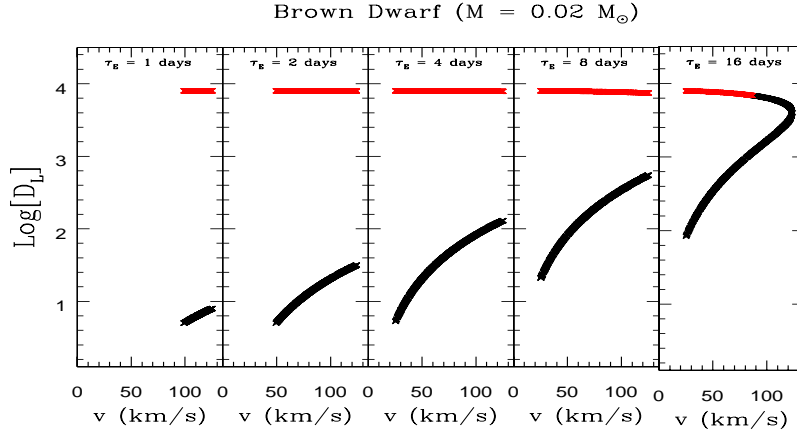


Fig. 1.— Logarithm of  $D_L$  vs  $v$  for a lens with fixed mass ( $0.02 M_\odot$ ) in the brown-dwarf regime. The field of background sources was placed at a distance  $D_S$  of 8 kpc. Each lens was given a randomly generated value of the transverse velocity,  $v$ , in the range  $25 - 125 \text{ km s}^{-1}$ . We assumed that the Einstein-diameter crossing time was 1 day in the leftmost panel, increasing by a factor of two in each panel to the right. For each lens, there are two possible values of  $D_L$ ,  $D_L^+$  and  $D_L^-$ . We computed both and show the results. If, for  $D_L^+$ , the value of  $b\theta_E D_S$  (with  $b = 0.1$ ) was smaller than  $10 R_\odot$ , we assumed that finite-source-size effects could be detected and plotted the point in red.

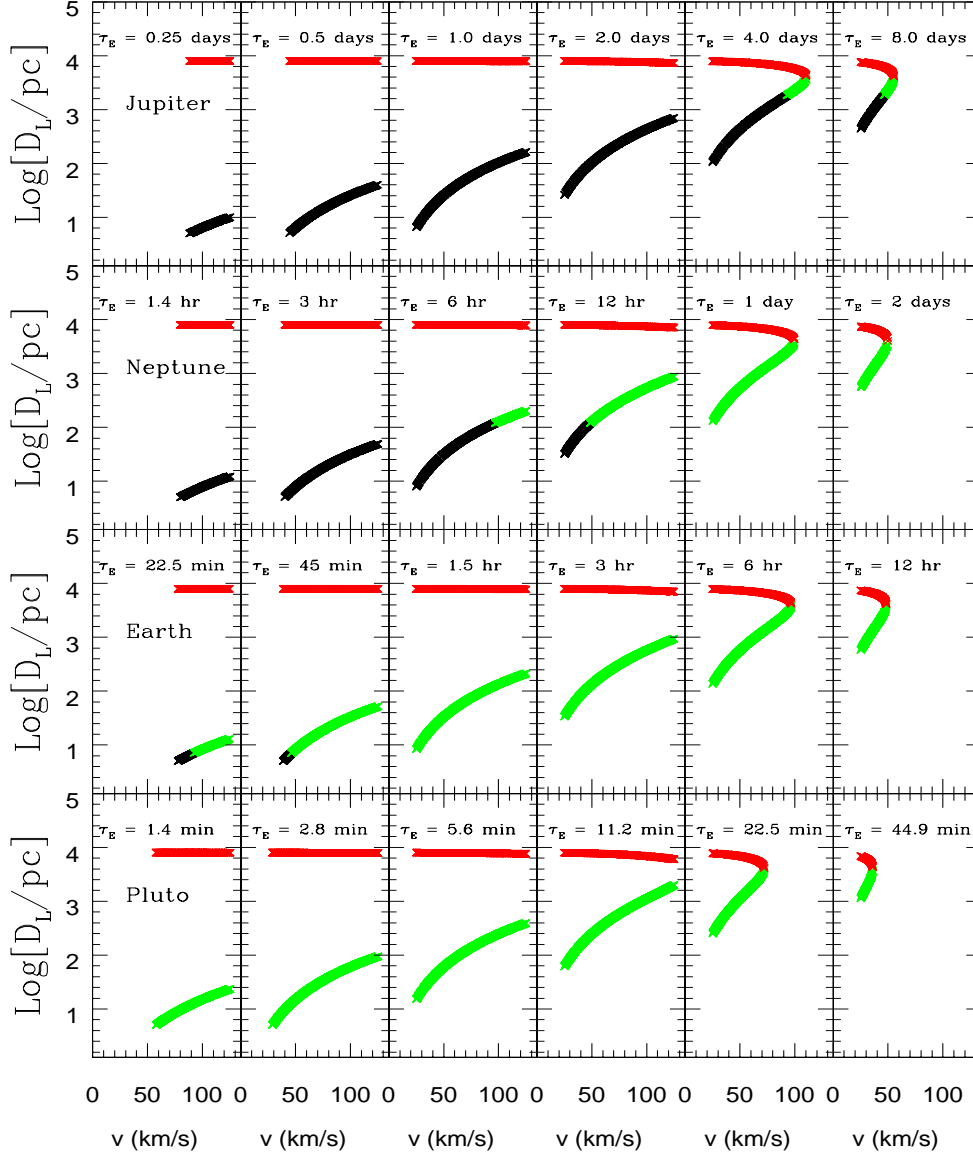


Fig. 2.— Each row consists of a set of 6 panels in which the logarithm of  $D_L$  vs  $v$  is plotted for a lens with fixed mass. The mass chosen is that of the planet which labels the row. For each planet the range of interesting time scales is shown. Note how this range is different for planets of different mass. If, for  $D_L^+$ , ( $D_L^-$ ) the value of  $b\theta_E D_S$  (with  $b = 0.1$ ) was smaller than  $10 R_\odot$ , we assumed that finite-source-size effects could be detected and plotted the point in red (green). See the caption of Figure 1 for additional details.

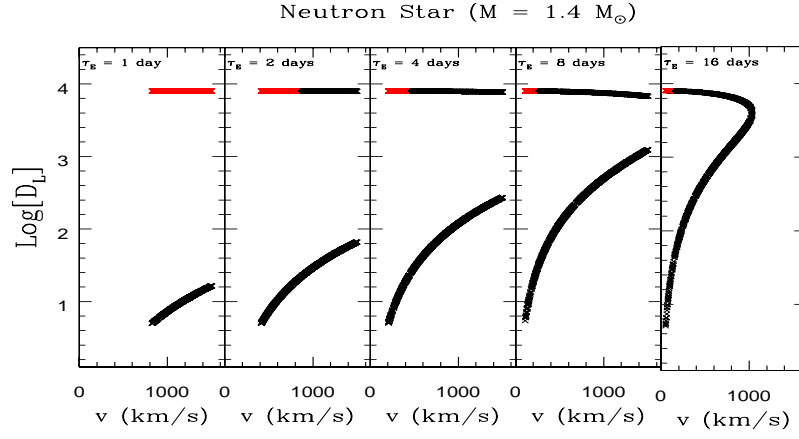


Fig. 3.— Logarithm of  $D_L$  vs  $v$  for a lens with fixed mass ( $1.4 M_{\odot}$ ). The Einstein diameter crossing time was 1.4 hours in the leftmost panel, increasing by a factor of two in each panel to the right. See the caption of Figure 1 for details.